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PRODUCTION AND CHARACTERIZATION OF POLYCARBONATE MICROSTRUCTURED POLYMER OPTICAL FIBER BRAGG GRATING SENSOR

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Abstract: We present the fabrication and characterization of a polycarbonate (PC) microstructured polymer optical fiber (mPOF) and the writing of a fiber Bragg grating (FBG) in it to obtain a polymer optical FBG sensor. The manufacturing process of the PC mPOF consists of multiple consecutive stages, such as casting of polymer granulates into a solid rod, machining and drilling of a 3-ring hexagonal lattice of holes into it, and finally drawing into fiber. We demonstrate that the obtained PC mPOF is photosensitive and FBGs can be conveniently inscribed into it, thereby enabling FBG-based temperature and strain sensing. The PC optical fibers are for some applications an attractive alternative to conventional materials used in POF fabrication, such as polymethyl methacrylate (PMMA). In general, PC can be used at temperature up to 120 °C and breaks at considerably higher strains than PMMA.

Key words: Bragg gratings, microstructured optical fibers, polycarbonate, polymers.

1. Introduction

Polymer optical fiber Bragg grating sensors have recently attracted increasing attention due to their unique characteristics [1]. The use of polymers instead of silica in optical fiber sensor technology offers several advantages, the most important perhaps being their higher elastic strain limits and reduced stiffness compared to glass fibers. Moreover, further characteristics of polymer optical fibers, such as biocompatibility, high flexibility in the production process, low densities, and elevated fracture toughness, are extremely attractive [1,2]. Polymer FBGs are therefore suitable for numerous engineering applications, e.g. strain and temperature sensing [3-4].

Exhibiting high transparency to visible light, polycarbonate optical fibers have been studied and used since the 1980s [5] and represent a natural alternative to PMMA, which is the most common material for POF fabrication. The use of PC is particularly attractive for some applications as its glass transition temperature (T_g) is among the highest in the class of plastics suitable for POF fabrication and, indeed, significantly greater than polymethyl methacrylate. PC can therefore be employed at temperature up to approximately 120 °C. Note that PMMA is limited to considerably lower temperatures, typically below 90 °C. Moreover, PC generally exhibits a yield strain comparable to that of PMMA and breaks at significantly higher strain values than the latter.

A microstructured polymer optical fiber is a waveguide where the light guidance is based on a patterning of small holes running along the whole fiber length [5-7]. To the best of our knowledge, only one journal paper on polycarbonate mPOFs has been published so far [8], in which the microstructured fiber was hollow-core and the polymer preform was fabricated via capillary stacking technique [7]. In addition, the use of PC-based mPOFs was mentioned in [9] and [10]. In both cases, though, neither detailed information about those fibers nor a specific optical characterization of them was reported. Here we present the experimental demonstration of a solid-core PC mPOF. The fiber manufacturing process involves multiple fabrication stages starting from commercial polycarbonate granulates. We characterize the polycarbonate fiber in terms of transmission loss and mechanical properties, and we further demonstrate that the fabricated PC mPOF is photosensitive and FBGs can be easily inscribed into it. This might enable high-temperature-resistant FBG sensing and thus help extend the range of technological applications for polymer optical fiber Bragg grating sensors.

2. Fabrication and characterization of PC mPOF FBG

2.1. Manufacturing of the PC microstructured polymer optical fiber

The fabrication process of the PC mPOF started from mechanical casting of commercial polycarbonate pellets. We used Makrolon® LED2245 from Bayer MaterialScience AG, with a T_g of 145 °C. This specific grade is optimized for applications requiring elevated transparency and high transmission over long optical paths [11]. The PC pellets were initially dried, and then cast into a solid rod with a height of 14 cm and a diameter of 7 cm. Casting of polycarbonate needed a strict control of temperature and pressure. In particular, it was necessary to apply relatively high temperatures, since PC might still contain some crystals at temperature even higher than 220 °C [12]. The cast preform was machined to eliminate any possible dishomogeneity in its near-surface volume. After machining, the final height and diameter of the PC solid rod were 10 cm and 6 cm, respectively. A hexagonal structure was then drilled into the PC preform. It consisted of three rings of air holes in a hexagonal arrangement. Figure 1 below shows both frontal (a) and lateral (b) views of the microstructured preform obtained from PC pellets after casting, machining, and drilling.

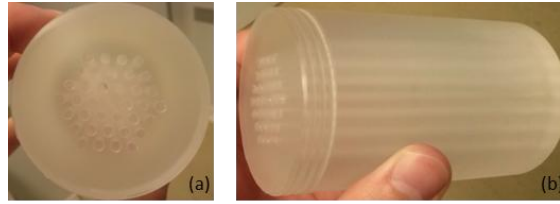


Fig. 1. a) Frontal view and b) lateral view of the PC preform with a 3-ring hexagonal hole arrangement.

The obtained preform was finally drawn to an intermediate PC cane, which was conveniently sleeved and drawn to fiber. The diameter of the final fiber was approximately 150 μm , whereas the core diameter was about 7 μm . Figure 2(a) displays a microscope image of the solid-core mPOF with the desired hole structure. The microstructured fiber was endlessly single-moded with average air hole diameter (d) and pitch (Λ) of 1.75 μm and 4.375 μm , respectively ($d/\Lambda = 0.4$).

2.2. PC mPOF characterization

2.2.1 Transmission loss

Fiber transmission loss profile was measured via cut-back measurement [7]. Cleaving was performed using an electronically controlled hot blade cleaver [3]. Figure 2(b) shows the transmission loss profile in the range of wavelengths between 550 nm and 900 nm. The minimum loss value (0.09 dB/cm) was measured at a wavelength of 832 nm. Transmission loss was found to be lower than 0.2 dB/cm within the ranges 575-860 nm and 875-900 nm, and, in particular, below 0.1 dB/cm for wavelengths from approximately 800 nm to 840 nm.

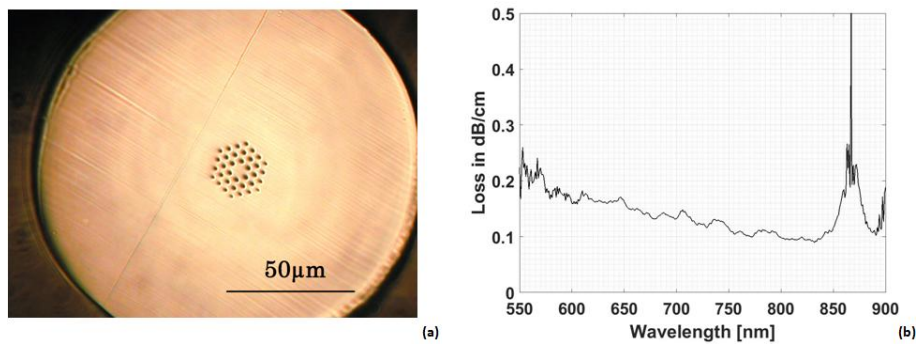


Fig. 2. a) Microscope image of the fabricated mPOF. b) Transmission loss profile between 550 nm and 900 nm.

2.2.2 Mechanical testing

A PC preform without microstructures, cast and machined in the same way as done for the PC mPOF, was also drawn down to fiber in order to perform uniaxial tensile testing on it. The average diameter of the final PC fiber was 276 ± 6 μm . Diameter measurements were carried out with a micrometer screw gauge and cross-checked via optical microscope. Both methods yielded values in reasonable agreement (± 5 μm). The homogeneous fiber was tested at a straining rate of 66% per minute in monitored open environment ($T = 22.4 \div 23.2$ °C, $RH = 21.7 \div 37\%$). Figure 3 below shows a typical stress-strain curve of the tested fiber, whilst Table 1 summarizes the results expressed in terms of yield point and break point, respectively. Note that stress and strain at fiber yield and

break points were calculated averaging the results from 6 different samples of the PC fiber. For each sample, the yield points were identified from the stress-strain curves applying Considere's Construction method [13].

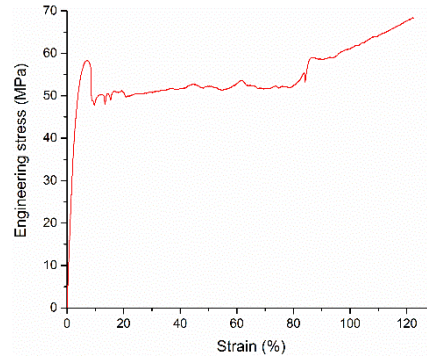


Fig. 3. Stress-strain curve measured in a uniaxial tensile test performed on the polycarbonate fiber.

On average, a high yield strain ($6.1 \pm 0.5\%$), at an engineering stress of approximately 61 MPa, was measured. This is in good agreement with Makrolon® LED2245 datasheet [14], which shows a yield strain and a yield stress of 6.0% and 65 MPa, respectively. Furthermore, in the uniaxial tensile testing the PC samples exhibited high strain values at break ($122 \pm 11\%$), which are consistent with the value of 115% reported in [14].

	Strain [%]	Error [%]	Engineering stress [MPa]	Error [MPa]
Yield point	6.09	0.50	61.3	0.9
Break point	122.3	10.9	68.4	5.3

Table 1. Yield and break points from tensile tests for mechanical characterization of the polycarbonate fiber.

It is important to notice that the high yield strain and elevated deformation at break measured for the polycarbonate fiber represent particularly useful properties when it comes to FBG-based sensing, especially for strain measurements. The Young's modulus (E) for the homogeneous polycarbonate fiber was also estimated. In order to calculate it, the engineering stress data within the strain region between 0.05% and 0.25%, i.e. the strain values recommended in ISO 527-1:1996 for plastics in tension, were considered. E was thus calculated to be equal to 2.0 ± 0.2 GPa, whereas the material datasheet [14] reports an average Young's modulus of 2.4 GPa. 2.0 GPa is lower than the average values of E reported in literature [15] for silica ($68 \div 74$ GPa) and PMMA ($2.2 \div 3.8$ GPa), thereby making this PC fiber potentially more sensitive to displacement forces [3].

2.3. FBG inscription in PC mPOF

The writing of the Fiber grating in the polycarbonate mPOF was carried out with a 50 mW CW HeCd laser operating at 325 nm (IK5751I-G, Kimmon). The detailed description of the experimental procedure can be found elsewhere [2-3]. Figure 4 below displays the reflection spectrum of a PC FBG measured at room temperature.

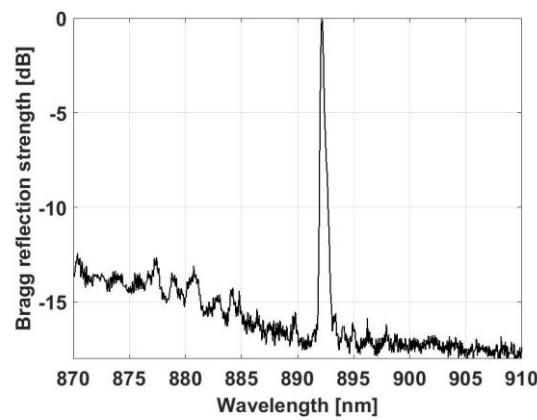


Fig. 4. Reflection spectrum of the PC FBG. The Bragg wavelength is 892.2 nm (reflection strength of 15 dB).

The Bragg wavelength for the PC mPOF fiber was 892.2 nm and the strength of the reflected peak was approximately 15 dB. At the Bragg grating wavelength (892.2 nm) the transmission loss was about 0.11 dB/cm, as shown in Figure 2(b). The successful inscription of the FBG in PC fibers demonstrates that polycarbonate is

photosensitive. As a result of the elevated T_g of polycarbonate, the obtained PC mPOF Bragg grating may potentially be used as a sensor for measurements of strain and temperature at relatively high temperatures.

3. Conclusions

In this paper we have presented the fabrication of a Bragg grating sensor in a PC mPOF manufactured by using a multistage process which starts from polycarbonate pellets. We have further characterized the polycarbonate fiber from both optical and mechanical points of view. Transmission loss profile for the solid-core PC mPOF was measured for the wavelength span of 550-900 nm, showing loss below 0.1 dB/cm within the range 800-840 nm. Moreover, the tensile behavior of the polycarbonate fiber was found to be in good agreement with the material datasheet [14]. This means that some advantageous mechanical properties that characterize polycarbonate can be successfully preserved throughout the fiber production process. Of particular importance, PC mPOF FBGs should theoretically be able to measure strain and temperature up to around 120 °C, whereas fiber Bragg grating technology based on PMMA is generally limited to temperatures below 90 °C.

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